- ⇒ Location (Distance from an identified reference girth weld.)
- ⇒ Orientation (~ o'clock position looking D/S). Photos required.
- ⇒ Dimensions of leak feature including orientation. Sketch or rubbing desirable.
- ⇒ Caused from Internal corrosion/external corrosion?
- ⇒ Located in Girth weld/longitudinal seam?
- ⇒ Located in manufacturing defect?
- ⇒ Located In longitudinal/transverse crack?
- ⇒ Located in mechanical damage. Sketch or rubbing mandatory.
- ⇒ Other

- Rupture:
  - ⇒ Gaping Split (Major longitudinal opening in the pipe but still intact looking similar to a fish's mouth.) Photo required with a scaled reference attached.
    - Orientation of split.
    - Description of fracture surface.
    - Estimate of percent of wall thickness remaining at the time of failure.
    - Length of Split.
    - Maximum width of split.
    - Describe any physical anomalies present on the pipe surface or on the fracture surface at the origin of failure. Photos required.
      - Internal Corrosion
      - External corrosion
      - Mechanical damage – Gouge
      - Mechanical damage – Dent
      - Manufacturing defect
      - Girth welding defect
      - Longitudinal welding defect
      - Arc burn
      - Longitudinal crack
      - Longitudinal crack clusters
      - Transverse crack
      - Transverse crack clusters
    - Actions taken to preserve the integrity of the ruptured pipe as required for future metallurgical testing. Include copy of Protocol. Photos required.
    - Actions taken to preserve the "Chain of Custody". Include copy of Protocol. Photos required.
  - ⇒ Major pipeline failure:
    - Length of pipe that failed.
    - Length of pipe recovered.
    - Number of pieces of pipe recovered

- Map of the fracture path. Include orientation (direction of flow, o'clock position)
- Estimated length of pipe not recovered and a description of processes implemented to effect recovery.
- Describe any physical anomalies present on the pipe surface or on the fracture surface at, or near the origin of failure. Photos required.
    - Internal Corrosion
    - External corrosion
    - Mechanical damage – Gouge
    - Mechanical damage – Dent
    - Manufacturing defect
    - Girth welding defect
    - Longitudinal welding defect
    - Arc burn
    - Longitudinal crack
    - Longitudinal crack clusters
    - Transverse crack
    - Transverse crack clusters
- Actions taken to preserve the integrity of the ruptured pipe as required for future metallurgical testing. Include copy of Protocol. Photos required.
- Actions taken to preserve the "Chain of Custody". Include copy of Protocol. Photos required.

10. Protective Coating:

- Describe condition of the coating at or near the origin. Photos required.
    - ⇒ Bonded
    - ⇒ Disbonded
    - ⇒ Damaged
    - ⇒ Porous
- Describe the conditions that exist under the coating in the event it is disbonded or damaged. Photos required.
    - ⇒ Dry and clean
    - ⇒ Presence of iron oxide
    - ⇒ Wet
    - ⇒ Dry with calcareous build-up.
    - ⇒ Wet with calcareous build-up.
- Extract samples of uncontaminated materials found under disbonded or damaged coating. (contamination is from the release) Photos required:
    - ⇒ Extract lab samples from under the coating U/S of and as close as possible to the origin.
    - ⇒ Extract lab samples from under the coating D/S of and as close as possible to the origin.
    - ⇒ Extract lab samples from under the coating at other locations in the vicinity of the incident that might be useful to obtain a full understanding of all activities that have taken place.

⇒ Take steps to preserve the identity and integrity of the samples so that they may be further evaluated by a laboratory if deemed necessary. ⇒ Prepare a sketch to show where all samples were taken. • Extract samples of coating materials found near the origin of failure. Photos required: ⇒ Extract coating lab samples U/S of and as close as possible to the origin. ⇒ Extract coating lab samples D/S of and as close as possible to the origin. ⇒ Extract coating samples at other locations in the vicinity of the incident that might be useful to obtain a full understanding of all activities that have taken place. ⇒ Take steps to preserve the identity and integrity of the samples so that they may be further evaluated by a laboratory if deemed necessary. ⇒ Prepare a sketch to show where all samples were taken.
11. Cathodic Protection:
• Evaluate the cathodic protection elements in place at and near the origin of failure: ⇒ Measure pipe-to soil potentials as close as possible U/S of the origin of failure. ⇒ Measure pipe-to soil potentials as close as possible D/S of the origin of failure. ⇒ Measure pipe-to soil potentials at other locations in the vicinity of the incident that might be useful to obtain a full understanding of all activities that have taken place. ⇒ Measure soil resistivities as close as possible U/S of the origin of failure. ⇒ Measure soil resistivities as close as possible D/S of the origin of failure. ⇒ Measure soil resistivities at other locations in the vicinity of the incident that might be useful to obtain a full understanding of all activities that have taken place. ⇒ Prepare a sketch to show where all readings were taken. • Describe the functionality of the closest CP elements U/S and D/S of the origin of failure: ⇒ Ground beds ⇒ Rectifiers ⇒ Anodes ⇒ Foreign line crossings ⇒ Other ⇒ Prepare a sketch to show where all descriptors above are located relative to the origin of failure.

12.5 Procedural Development

After the initial data collection and site evaluation, a written procedure to address the following steps should be developed:

- Interim Measures: Repair procedure; interim operational plan; safety considerations; communication plan and protocol
- Return to Service Plan Development: Evaluation of line segment for additional SCC; required metallurgical/geotechnical investigations and reporting; conformance with IM plan and protocols; requirements for additional ILI, direct examination and/or direct assessment.

This plan is summarized in a written report suitable for distribution to regulatory/public groups. Adjustments are made as required and the Return-to-Service Plan finalized.

- Incident Follow Through: Monitoring of performance and/or additional investigations as required; QA/QC plan and reporting requirements; review of all Engineering Evaluations.
- Incident Closeout: Final delivery of the incident evaluation report with associated Engineering and laboratory evaluations; adjustment to the Operations Manual as required; adjustment to linewide SCC threat assessment as required; long-term communications plan.

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13 Summary

13.1 Conclusions

The following conclusions are based on the findings of this study and should be considered "point in time" (i.e. based on the industry's current understanding, or lack of understanding, of the phenomena known collectively as SCC). Additional research and data compilation is expected in this area, and the study conclusions should be revised accordingly (see Section 9, and particularly Section 9.3.4 and Figure 9-1 for research priorities).

In general, the emphasis for dealing with SCC is on awareness, qualification of personnel, planning, and documentation. It is recognized that there are currently no plans or actions that can adequately address all situations, especially given the current state of data and knowledge concerning SCC.

13.1.1 Design

- Linepipe - Although much research has been done on linepipe steel, no specific conclusions are made as regards to grade or metallurgy. However, manufacturing processes that minimize residual tensile stresses in the pipe should be considered.
- Coating – FBE, which is the modern coating of choice, appears to offer good resistance to SCC when coupled with an effective and complete specification for application. There are other coatings that potentially offer good resistance to disbondment that could also be considered, but have less experience industry wide. For new pipelines, tape coatings should not be used where there is a risk for SCC—and, at the least, tape coatings should be critically assessed to ensure against disbondment. For recoatings FBE is usually not practical, so the type of coating should be carefully considered to ensure that the recoated section achieves full protection, and perhaps some additional research is indicated in this area.
- Alignment – the operator should consider completing an initial SCC threat assessment, using an internal evaluation technique (such as that described below) to prioritize segments, which have a high susceptibility to SCC. Where possible, consideration should be given to additional QA/QC oversight of coating installation for these segments, additional protection against holidays, and realignment where possible in high threat circumstances.

13.1.2 Construction

- Coating installation and repair specifications, citing surface preparation and application procedures to ensure bonding and quality coatings, should be considered for inclusion in the contract documents.
- QA/QC procedures for coating installation should be implemented by qualified personnel, trained in NACE or similar procedures.

13.1.3 Operations

- Procedures to ensure the operating temperature remains within design limits of the coating and bonding mechanism should be developed.
- Operational awareness of the detrimental effects of temperature excursions should be available in the operational procedures, with accompanying procedures for engineering evaluation in the event of temperature excursions.
- When SCC is found, an immediate response for gas pipelines is required, which necessitates a reduction in pressure. In lieu of other information, the pressure reduction will be to a value not exceeding 80% of the pressure at the time the anomaly is discovered. In any case, and for both gas and liquid pipelines, the anomaly should be critically evaluated for determination of the safe operating limits based on the best available data. The daily pressure history should be available in a form conducive to engineering evaluation.

13.1.4 SCC Awareness Program

- An operator education program, explaining the causes and identification of SCC to field personnel, should be developed and readily available.
- A core cadre of operator personnel should be NACE, or similar professional organization, qualified, and designated in operating plans as corporate resources for addressing SCC.
- To the extent possible and appropriate, operator engineering personnel should have continuing education in the areas of SCC and be encouraged to keep abreast of research in SCC.

13.1.5 SCC Detection through ILI

- A written document that identifies the practicality of ILI tools in detecting SCC for the operator lines should be completed for each major operating pipeline. Although, and as discussed in this report, SCC detection in gas pipelines using ILI may not be currently considered practical, at least by some operators and for some lines, the tool development is rapidly advancing and close attention should be focused on ILI capability in this regard.
- An internal database that tracks the effectiveness of an ILI tool in detecting SCC on the operator's lines should be developed and regularly updated. Error bands for detection should start with vendor data and be refined through the use of this database. The error bands should be included in SCC threat assessment techniques. As discussed in this report, this may currently be problematic for most gas pipelines since the tool capability is probably not compatible with a detailed effectiveness tracking procedure at this time, but the tool development is rapidly advancing and close attention should be focused on ILI capability in this regard.

13.1.6 SCC Detection through Direct Examination

- Anytime the pipe is uncovered, the pipe assessment should include consideration of the possibility of SCC.
- Direct Examination methods should be reviewed to ensure that SCC awareness is included in all direct examination techniques. "Triggers" for more detailed SCC techniques, such as coating disbondment, should be identified.
- Written procedures for examination of pipe segments with potential SCC should be developed.
- Personnel with experience and/or detailed education of SCC should be included in all investigations when there is a possibility of SCC.
- Data collection forms should be developed, completed and stored for each SCC Direct Examination threat assessment.
- An engineering evaluation procedure should be developed and followed for determination of the SCC threat. It is recognized that there is no single formula or software code that will address this complicated technical evaluation. Further, different operators may find different approaches are more appropriate to their circumstances. The engineering procedure should acknowledge this and allow for different metallurgical, environmental, and mechanical factors as well as consideration for a change in approach as understanding progresses. This could be done as part of a more general corrosion engineering procedure. Nevertheless, the engineering approach should be documented and readily available throughout the organization to ensure a base level of consistency in all pipelines within the operator's purview.

13.1.7 SCC Remediation

- Specific repair techniques should be developed and updated as required for SCC. The repair techniques should clearly identify the threat assessment limits for which the repair is applicable.
- Operating procedures that mitigate the SCC threat until repairs are completed should be developed, again with clearly identified threat assessment limits for which the procedure is applicable.
- Engineering evaluation procedures that are adjusted based on the repair evaluation should be developed and followed.

13.1.8 IM Program – SCC

- The Protocols should be examined to ensure that the IM plan meets all minimum requirements.
- Historical evidence of SCC should trigger specific additional requirements for the applicable lines.

13.1.9 Response to In-Service Failure

- Any in-service failure investigation should consider the possibility of SCC causing or exacerbating the failure occurrence.
- Qualified staff knowledgeable in the causes and identification of SCC should be detailed to respond to an incident that may include SCC.
- Data collection forms should be developed, completed and stored for each SCC failure investigation.
- SCC examinations should include plans for metallurgy examination, immediate reduction of pressure and/or other mitigative means, and a plan to return to service that includes not only an evaluation of the site but also consideration of additional areas which have similar threat indicators.

Appendix A
Stress Corrosion Cracking Research Gap Analysis

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A Research Gap Analysis

A.1 Mechanisms of SCC

A.1.1 Mechanism of High pH SCC

There is almost universal agreement that crack initiation and growth in the high pH environment occur by selective dissolution of the grain boundaries, while a passive film forms on the remainder of the surface and on the crack sides to prevent corrosion at those locations. When an unstressed, polished surface of line-pipe steel is exposed to the high pH carbonate/bicarbonate environment at the appropriate potential for SCC, etching of the grain boundaries occurs with no noticeable corrosion of the grain faces (Parkins 1994). A strong correlation has been found between the maximum rate of crack growth and the maximum corrosion rate that can be sustained in that environment (Parkins 1987). The reason for preferential attack at the grain boundaries is thought to be related to some kind of chemical segregation or precipitation at the grain boundaries, but no direct evidence of either has been found.

Additional basic research into the fundamental mechanism of high pH SCC probably would not be justified.

A.1.2 Mechanism of Near-neutral pH SCC

Some researchers have suggested that the mechanism of initiation of near-neutral pH SCC may be different from that of crack growth (Fessler and Krist 2000). Neither stage of the cracking process is as well understood as is the mechanism of high pH SCC.

Crack Initiation. The mechanism for stress corrosion crack initiation in the near-neutral pH environment is not completely understood, but evidence from field failures suggests that corrosion pits might be a common site for crack initiation. In some cases the cracks were found in broad, shallow corroded areas. More commonly, there was very little corrosion visible to the naked eye, but very small corrosion pits at each crack have been seen with microscopic examination. Thus, many researchers believe that a corrosion pit may act as a stress raiser to initiate the stress corrosion crack. Also, the environment at the bottom of a pit will become more acidic.

Initiating near-neutral pH SCC in the laboratory under stressing conditions that are representative of those on an operating gas pipeline has proven very difficult. In experiments with polished, smooth specimens, researchers at CANMET produced clusters of transgranular cracks that appear very similar to near-neutral pH stress-corrosion cracks that have occurred in the field (Elboujdainia et al. 2000). The earliest cracks to appear initiated at corrosion pits that formed around nonmetallic inclusions, and later cracks grew from corrosion pits that formed randomly on the surface. However, cracks initiated only in tests that involved many thousands of high-amplitude (low-R) stress cycles, a situation that is not typical of gas pipelines. Tests with more realistic stressing conditions did not produce cracks. Therefore, there is a concern that the tests that produced cracks may have involved corrosion fatigue rather than SCC.

Several mechanisms for producing shallow crack-like features at the surface of a sample of line-pipe steel under more realistic loading conditions have been demonstrated by King, et al. (2001). Expanding upon previous work by Wang, et al., (2000) which showed that corrosion pits formed preferentially along the heavily deformed metal in scratches on the surface, it was then shown that the rows of corrosion pits would join and preferentially grow deeper if the scratches were perpendicular to the direction of the tensile stress. Chu, et al. (2004) showed that preferential corrosion occurs at the boundaries of pearlite colonies, and transgranular crack-like features can grow from such surface attack.

Another possible mechanism for initiation involves small cracks oriented approximately 45 degrees to the direction of the tensile stress that were produced on specimens that had been subjected to a series of cyclic stresses patterned after a typical 20-year service life. Presumably, the cracks formed where persistent slip bands intersected the surface of the specimen.

Crack Growth. Whereas a dissolution mechanism for high pH SCC was supported by the agreement between measured crack velocities and those that would be predicted from Faraday's Law and current densities measured in polarization experiments, the same did not appear to hold for near-neutral pH SCC. Anodic current densities measured near the open-circuit potential in near-neutral pH environments were on the order of 10 microamps per square centimeter, which would correspond to a crack velocity of about 10^{-8} mm/sec according to Faraday's Law (Parkins 1998). Whereas that crack velocity is considered to be a reasonable estimate for the maximum rate of crack growth in the field and also corresponds to typical velocities measured on laboratory specimens subjected to realistic stressing conditions, there were reports of measured crack velocities as high as 10^{-6} mm/sec. Therefore, people looked for other mechanisms that might explain a crack velocity that was 2 orders of magnitude larger than would be produced by dissolution according to Faraday's Law. Other mechanisms that are known to produce transgranular fractures in carbon steels include fatigue, corrosion fatigue, and hydrogen embrittlement, the latter mechanism being the one that has been embraced by most researchers.

The hydrogen theory was supported by the results of a variety of slow-strain-rate experiments. For example, Mao, et al. (1998) showed that precharging specimens with hydrogen prior to testing in the near-neutral pH environment caused a decrease in the final reduction in area, which was assumed to indicate more severe SCC. However, as is shown in Figure A-1, the precharged specimens did not exhibit lower ductility when tested in air, so some synergistic effect between the hydrogen and the corrosive environment may be indicated.

More evidence for synergy between corrosion and hydrogen was developed by Parkins (1999) when he used slow-strain-rate tests (SSRT) to measure reduction in area (RA) as a function of potential and compared those results with anodic current densities and hydrogen contents (as determined from permeation experiments) over the same range of potentials. As is shown in Figure A-2, the dip in RA, which presumably corresponds to the region of SCC, between –550 and –700 mV occurs where there are small but significant amounts of both corrosion and hydrogen. At less negative potentials, the hydrogen concentration drops to insignificant levels, and the RA rises to high values, indicating no more SCC. At potentials between –700 and –750 mV, the corrosion rate drops to insignificant levels and there is a local maximum in RA.

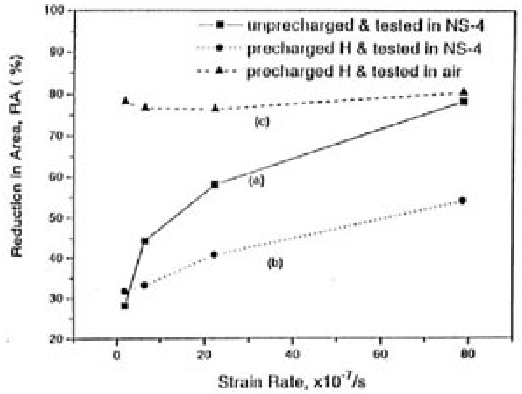

Figure A-13-1 Effect of Precharging with Hydrogen on Reduction in Area of SSRT Specimens Tested in NS4 and Air

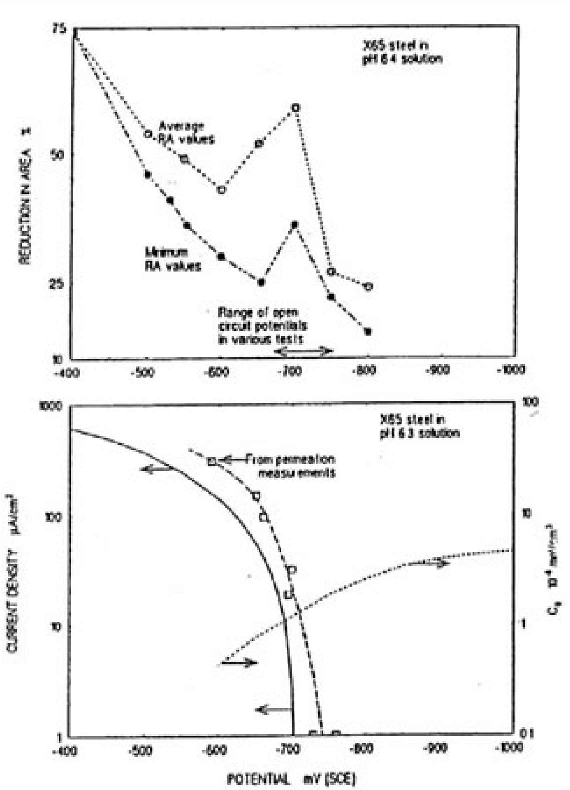

Figure A-13-2 Correlation Between Potential for Most Severe Near-neutral pH SCC and the Narrow Potential Range Where Both Dissolution and Hydrogen Entry Occur at Significant Levels

The reason for the continual decline in RA at still more negative potentials is not clear. By analogy to the high pH SCC situation, one might believe that the decrease in RA at very negative potentials is due to some hydrogen effect that only occurs at very high levels of continuous plastic deformation and therefore is not relevant to an operating pipeline. Parkins (1998) has indicated that some SSRT specimens with RA values as low as 30 percent contained no detectable cracks, indicating that some embrittling, but not cracking, mechanism was operative. In fact, experience tells us that cathodically protected pipelines do not experience cracking problems where the potentials are adequate and the steel is not shielded from the cathodic-protection currents. An alternate point of view that is held by some researchers is that the SCC reaction continues to negative potentials in laboratory experiments because the stirring prevents the formation of an alkaline environment at the cathode, whereas that alkaline environment in the field will not support SCC at those potentials. Experiments that do not involve high amounts of plastic deformation (e.g. cyclic-load tests rather than SSRT) with stirred and stagnant environments will be required to clarify the significance of the low RA values at very negative potentials.

Even though a hydrogen-based theory is popular with most researchers in this field, there are several reasons that dissolution should not be ignored as possibly a significant part of the mechanism of near-neutral pH SCC:

1. Although hydrogen can cause delayed brittle fracture in very-high-strength steels at stresses below the yield strength, that phenomenon has not been observed in steels with yield strengths below 80 ksi (Fessler, Groeneveld, and Elsea 1973). Hydrogen can reduce the ability of lower-strength steels to tolerate large amounts of plastic deformation, but

pipelines do not experience large amounts of plastic deformation in service. It might not be coincidence that all experiments that seem to demonstrate an effect of hydrogen on SCC have involved SSRT.

2. The high crack velocities on the order of 10^{-6} mm/sec have only been observed on specimens that have been subjected to low-R (typically about 0.5) stress fluctuations. ("R" is "…the ratio of the minimum to the maximum load for each cycle" (King et al, 2001). As is described later in this report, there is reason to believe that the mechanism at low R may be corrosion fatigue rather than SCC. Laboratory experiments at R values of 0.85 and above, which are more typical of gas pipeline operation, usually produce crack velocities of 10^{-8} mm/sec or lower, which would not be inconsistent with Faraday's Law.

3. The anodic current densities that have been used with Faraday's Law were determined on undeformed coupons of steel. However, the steel at the tip of a crack (the plastic zone) is highly deformed. There are some reasons to believe that heavily deformed steel will corrode more rapidly than undeformed steel. It was mentioned previously that corrosion pits formed preferentially in the deformed metal in scratches on the surface of coupons. Foroulis and Uhlig (1964) determined that 50 percent cold work could increase the corrosion rate of carbon steels in 0.1N HCl by about 7 times, and subsequent aging at 100°C for a few hours could double the rate again. However, the effect of cold work on corrosion rate was not observed in neutral solutions. Whether there is an effect at the pH levels between 5 and 7 is not known. It also has been speculated that the pH inside the crack could be much lower than outside, which would tend to magnify the effect. Incidentally, Uhlig (1976) also showed that anodic dissolution enhances the room-temperature creep of cold worked iron and steel, and Oriani (Oriani and Josephic 1981) showed that hydrogen also enhances the room-temperature creep of steel, suggesting the possibility of several synergetic effects at the tip of the crack.

4. Another way that the corrosion rate at the crack tip might be accelerated is due to the fact that the hydrogen that is in the steel will preferentially move into the plastic zone. Mao, et al. (1998) have shown that charging X52 and X80 steels with hydrogen changes the shape of the polarization curves to suggest an increase in corrosion rate due to hydrogen in dilute bicarbonate solutions and NS4. However, while the effect was pronounced at positive potentials, it is difficult to tell from the published data whether the effects near the open-circuit potential, where near-neutral pH SCC occurs, were significant.

5. Near-neutral pH stress-corrosion cracks from the field or from laboratory tests invariably contain a considerable amount of corrosion product.

If hydrogen truly is an important factor in near-neutral pH SCC, a better understanding of the role of hydrogen might lead to better site-selection models if soil environments could be ranked with respect to their propensity to introduce hydrogen into the steel under free-corrosion conditions.

A.2 Causes of SCC in Pipelines

SCC is known to occur in many metallic alloys and polymers that are exposed to a wide variety of environments. However, for each material, there are a limited number of environments that can cause SCC, and certain levels of stress or stress fluctuations are required. Thus, it is a process that involves three interrelated factors: a susceptible *material* exposed to a specific *environment*, and subjected to specific ranges of *stress*. Significant alteration of any one of those factors is sufficient to prevent SCC.

A.2.1 Causes of High pH SCC

Environment. The effects of various environmental factors on high pH SCC are reasonably well understood. High pH SCC has been observed in solutions with various ratios of sodium carbonate to sodium bicarbonate ranging from almost pure sodium bicarbonate to almost pure sodium carbonate (Parkins and Fessler 1978). Those ratios correspond to a pH range from about 8 to 10. SCC is most severe in highly concentrated solutions, but it has been observed in less concentrated solutions having concentrations about one third those usually used in laboratory experiments (Parkins and Zhou 1997).

Although high pH SCC has been observed at temperatures ranging from 20°C to about 90°C, the crack velocity is much higher at the higher temperatures, and it decreases exponentially with decreasing temperature (Fessler 1979).

High pH SCC will occur only in a narrow range of potentials, the specific range depending upon solution composition and temperature. As is shown in Figure A-3, the width of the range decreases as the pH increases (Parkins and Fessler 1978). The width of the potential range for SCC also decreases with decreasing temperature, as is shown in Figure A-4 (Fletcher et al. 1982). In general, the critical potential range for high pH SCC is between the open-circuit potential and cathodic-protection potentials. Such potentials can be achieved on a pipe with normal levels of cathodic protection due to partial shielding of the cathodic-protection current by a disbonded coating. However, laboratory experiments have shown that a heavy oxide, such as mill scale, on the steel surface is necessary to hold the potential in the critical range for appreciable times. If the surface is nearly free of oxides, the potential under the disbonded coating will rapidly move to more negative values in the highly conductive carbonate/bicarbonate environment (Parkins and Fessler 1986).

Stress. The role of stress, including stress fluctuations, is thought to be the promotion of creep deformation at the tip of the crack, which results in rupture of the comparatively brittle passive film, thus exposing bare metal to the corrosive action of the environment. The stress or stress intensity must be above a certain threshold level to produce a sufficient strain rate to exceed the passivation rate. The threshold stress can vary considerably from batch to batch of steel and even for different thermal and mechanical histories of a given batch (Fessler and Barlo 1984).

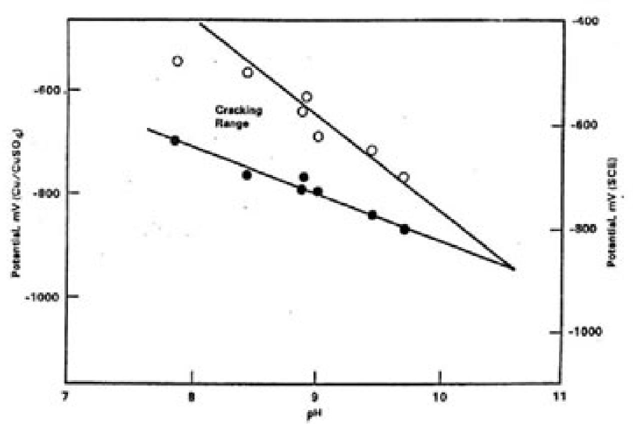

Figure A-13-3 Effect of pH on the Range of Potentials in Which Intergranular SCC can Occur in Line-Pipe Steels at 75°C

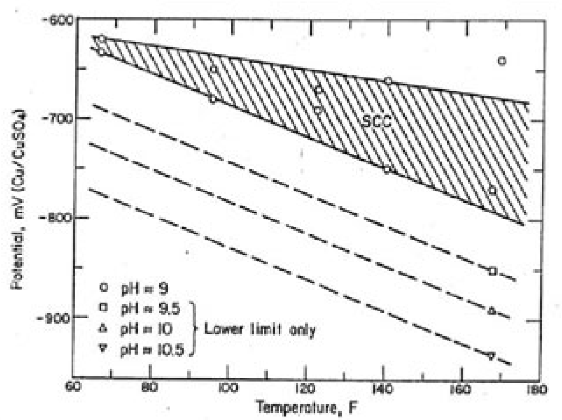

Figure A-13-4 Effect of Temperature on the Critical Potential Range for High pH SCC

The threshold stress can be reduced considerably if small-amplitude, low-frequency stress fluctuations are superimposed on the mean stress. The amount of reduction varies from steel to steel and varies with the amplitude and frequency of the fluctuations. One of the most dramatic effects, which is illustrated in Figure A-5, was a decrease of the threshold stress to 40 percent of the yield strength through the application of fluctuations as low as 1.5 percent of the mean stress twice a month (Fessler 1976).

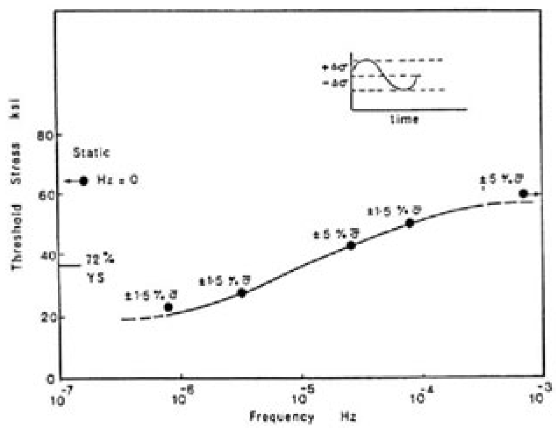

Figure A-13-5 Effect of Low-Amplitude (High-R) Stress Cycles on the Threshold Stress of an X52 Steel Exposed to a 1N Solution Carbonate + 1N Sodium Bicarbonate Solution at 75°C and –650 MV (SCE)

Steel. Although analyses of pipe that failed in service have not revealed any obvious correlations with steel composition, grade, or microstructure (Fessler 1976), there is direct evidence from laboratory studies that certain batches of steel are much more resistant to SCC than others. There are two important parameters associated with steel susceptibility: (1) crack growth rate and (2) threshold stress or stress intensity. Those parameters may be controlled by different mechanisms and, therefore, might not be directly related to each other. In other words, a given steel might have a relatively high threshold stress compared to that of another steel, but the crack growth rate above the threshold stress might not necessarily be lower. For example, in the case of high pH SCC, the crack growth rate probably is primarily controlled by the rate of dissolution, while the threshold stress may be more directly related to the creep resistance of the steel.

In a 1N sodium carbonate + 1N sodium bicarbonate solution at 75°C with a constant applied load, the threshold stresses of 10 different steels were found to be nearly equal to the yield strengths, the maximum differences being about 15 percent (Parkins, Belhimer, and Blanchard 1993). The range of yield strengths was from about 30 to 70 ksi.

Parkins, Belhimer, and Blanchard (1993) correlated the reduction in threshold stress with the strain-hardening behavior of the steel when subjected to cyclic stresses superimposed on a monotonically increasing stress. As is shown schematically in Figure A-6, the superimposed cyclic stress (typically on the order of 2 to 11 ksi) caused plastic deformation to start at much lower levels of mean stress, and the slope of the plastic portion of the stress-strain curve changed abruptly at a certain stress. That stress, where the slope became very low, correlated strongly with the threshold stress as measured under the same magnitude and frequency of superimposed fluctuating stress (see Figure A-7).

Thus, the susceptibility of a steel to high pH SCC appears to be controlled by its cyclic strain-hardening behavior or cyclic creep behavior and possibly by chemical segregation. Unfortunately, the relationships of cyclic strain hardening or cyclic creep or corrosion behavior to microstructure and impurity distribution are not known nor are the relationships of the critical microstructural features and impurity distribution to composition and processing. An understanding of those relationships will be needed to enable one to design steels that are highly resistant to SCC.

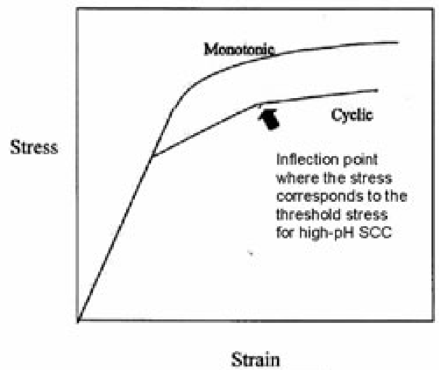

Figure A-13-6 Comparison of Typical Stress-Strain Curves Produced with Monotonic Loading and with Cyclic Loads Superimposed on the Steady Loads

A.2.2 Causes of Near-neutral pH SCC

Environment. The chemical environments surrounding stress-corrosion cracks in the field have been studied far more extensively for near-neutral pH SCC than for high pH SCC. Hundreds of trapped water samples from under coatings and soil samples near the pipe have been analyzed. The results have been summarized by Jack, et al. (2000). The water samples have been very dilute, containing some bicarbonate ions plus lesser amounts of carbonate, chloride, and sulfate. The pH usually has been between 6 and 7. The major cations are sodium, calcium, potassium, and magnesium. Soils near SCC sites have been found to contain 4 to 23 percent CO_2 (Delanty and O'Beirne 1992).

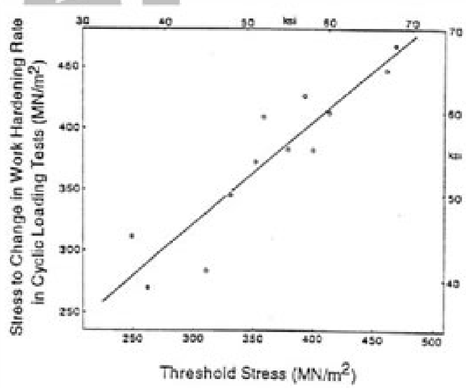

Figure A-13-7 Correlation of the Threshold Stress for High pH SCC and the Stress at which the Work-Hardening Rate in Cyclic-Loading Tests Suddenly Decreases

The fact that the pH of the trapped water is slightly below 7 suggests that little if any cathodic-protection currents reach the pipe where near-neutral pH SCC occurs. Thus, it occurs near the open-